Neutrino Beam Composition - I

Extraction of ν_e Component

Introduction

The neutrino beam is composed of four major components which all originate in the beam dump, 38m from the emulsion target: ν_μ (prompt, i.e. from charm decay), ν_μ (non-prompt, from π and K decays), ν_e, and ν_τ. The neutrino interactions are composed of these three parts, with both charged-current (CC) and neutral current interactions (NC). In addition, the neutral current interactions of all flavors are considered in this analysis as a separate, fifth category. It is important to characterize the beam components from data in terms of their energy spectrum and relative number. In the data, there are two easily and relatively unambiguous classes of events:

1 The ν_μCC interactions - labelled "**μCC**"
2 The events that are *not* ν_μCC interactions - labelled "***e*CC+NC**"

The "**μCC**" set is defined as those events that have at least one muon positively identified in the muon ID proportional tubes, which means at least 4 planes recording the muon track. There are some cases where less than 4 planes have hits, but the event has been identified as containing a muon with high probability (>90%) by human scanning. This is the purest set of events. The next easily definable set is the complement of the muon set, "***e*CC+NC**", containing no events in common with "**μCC**", but with an additional requirement of at least 2 GeV of energy, defined as the sum of the energy of all the clusters, *not* simply the sum of all energy in each block. As the label suggests, this set is mostly composed of ν_eCC events, plus most of the recorded NC events. There may be a contamination from ν_μCC events where the muon has not been tagged. Also, the "**μCC**" distribution has one "mip" = 0.70 GeV subtracted to compensate for the average energy deposited by the muon.

The problem addressed in this analysis is to determine the relative number of all five "components" listed above from the data itself, *i.e.* the result is four numbers. The only experimental quantities that will be used explicitly are: (1) the muon momentum from tracking through the analysis magnet, (2) the total energy in the calorimeter, and (3) the muon ID system providing a yes/no ID for each track in an event. This analysis generally uses the distribution of these quantities over selected data to extract all but the ν_μCC events since without emulsion information there is poor discrimination on an event-by-event basis.

Analysis

Three different analyses where performed on the data from Period 3 and 4 using the improved gain balance for the calorimeter channels. Only events identified in station 4 or events downstream of module 4 (*e.g.* interactions in the CS or SFT) were used in all analyses. The two periods were not separated as the statistics would be too poor.

Method 1

This method takes the data set "***e*CC+NC**" and subtracts the weighted "**μCC**" distribution bin-by-bin, and so assumes that the "**μCC**" distribution has the same shape as the true NC calorimeter distribution. This should be an excellent approximation. Thus, define:

$$\text{“}e\text{CC”(1)} = \text{“}e\text{CC+NC”} - k \times \text{“}\mu\text{CC”}$$

It is necessary to estimate k using physics and experimental input. Assume the trigger efficiency for NC (μCC) reactions is 0.86 (0.96) and the total selection efficiency is 0.80 (0.86). The averaged NC rate is 0.35 relative to the CC rate. The number of NC interactions in the "***e*****CC+NC**" set must be larger than the events from the **"μCC"** sample only, and must be less than (or equal to) the events assuming 45% ν_e and ν_μ and 10%ν_τ. Hence the value of k is bounded by :

$$\frac{\varepsilon_{NC}}{\varepsilon_{\mu CC}} \cdot \frac{\sigma_{NC}}{\sigma_{\mu CC}} < k < \frac{\left(N_{\mu CC} + N_{eCC} + N_{\tau CC}\right)}{N_{\mu CC}} \cdot \frac{\varepsilon_{NC}}{\varepsilon_{\mu CC}} \cdot \frac{\sigma_{NC}}{\sigma_{\mu CC}}$$

$$0.25 < k < 0.60$$

For a central value, pick $k = 0.4 \pm 0.15$. There are two ways to estimate the number of muon CC interactions in Station 4, $N_{\mu CC}$, in this data set. One can use the number of events found in Station 4 [41] or one can sum the total number of interactions at all stations [202] and compute the average for Station 4 weighted by the mass×pot, [202×(62kg/280kg) = 45].

The "***e*****CC+NC**" samples for all stations are shown in Figure 1 and the **"μCC"** distribution is shown in Figure 2. The k×**"μCC"** sample is subtracted bin-by-bin, and the result is shown in Figure 3. The total number of events in the subtracted set, **"*e*CC"**(1), is 57 events ±7(sys) ±8 (stat). The mean energy is 33.6 GeV. Note that this distribution cannot be directly compared to the **"μCC"** p_μ distribution because: (a) there are absorption corrections for Station 4 events (~25%) and (b) the spectrum is not due only to the $e^\pm$, but has the additional recoil component with a distribution like **"μCC"**.

Method 2

The second method is simpler, but relies to a small extent on information from the Monte Carlo. A 20 GeV cut is placed on both the "***e*****CC+NC**" set and the **"μCC"** set. The estimate for the number of ν_eCC events is given as :

$$N_{eCC}(2) = \left(N_{eCC+NC}(E > 20) - N_{\mu CC}(E > 20)\right) \cdot f_{MC}^{-1}$$

Where f_{MC} is the fraction of ν_e events that are lost with a 20 GeV cut and is equal to 0.88. There are 42 events in the "***e*****CC+NC**"(E>20) sample and 6 events in the **"μCC"**(E>20) set giving the estimated NC interactions with Method 2 as 42 events. The Monte Carlo distributions for the calorimeter energy in ν_e and ν_μ interactions is shown in Figure 4. It appears from the MC distributions that a 20 GeV cut has a smaller effect than in the data, simply because the MC distributions favor higher energy. If this were indeed true, the correction factor, f_{MC}, would be smaller and so the estimate, $N_{eCC}(2)$ would be larger.

Method 3

The recognition of an ν_e CC interaction in the spectrometer is not as reliable as a ν_μ CC interaction since other processes such as π^0 decay and hadronic interactions can deposit energy in the calorimeter. However, a high-energy $e^\pm$ created in emulsion at Station 4 has certain characteristics visible in the spectrometer that can be used to discriminate these interactions. The two most important indicators are:

♦ a track in the SFT (often ≥ 2 mip pulse height) can be made which points to the highest energy cluster in the calorimeter

♦ e^+e^- pairs of energy > 1 GeV visible in the DCs on each side of a calorimeter cluster with an energy > 10 GeV

The "***e*CC +NC**" data set for calorimeter energy, E>2 GeV, and events in Station 4, was inspected to determine an estimate for the ν_e CC interactions. Each event was visually inspected to see if the two criteria above were met, and if so, was included as a ν_e interaction. From a total of 82 events, 40 were chosen as likely ν_e interactions. The average energy for this selected set is 46 GeV. Figure 5 shows the energy distribution for this data.

Discussion

These three analyses yield 57, 42 and 40 events for the number of ν_e CC interactions in Station 4 for Periods 3 and 4. In principle, *Method 1* may be more reliable as it is derived from the data with only weak assumptions about the efficiencies included in the calculation. Recall that the total number of ν_μ CC interactions for this data set is 41. One might conclude that the number of non-prompt ν_μ CC interactions is small, <30%. If this analysis is continued further, the number of NC interactions can be estimated by simply subtracting the number of events in the **"*e*CC"**(1) set [57]from the number of events in the **"*e*CC+NC"** set [82] giving 25 events. As a consistency check, one can add the ν_μ CC and ν_e CC numbers times the production cross section ratios to give :

$$\text{number in } \textbf{“NC”} = (57+41)\times 0.35\times 0.75 = 26 \text{ events}$$

where the factor 0.75 is due to the ratio in efficiencies for having the events in the final sample.

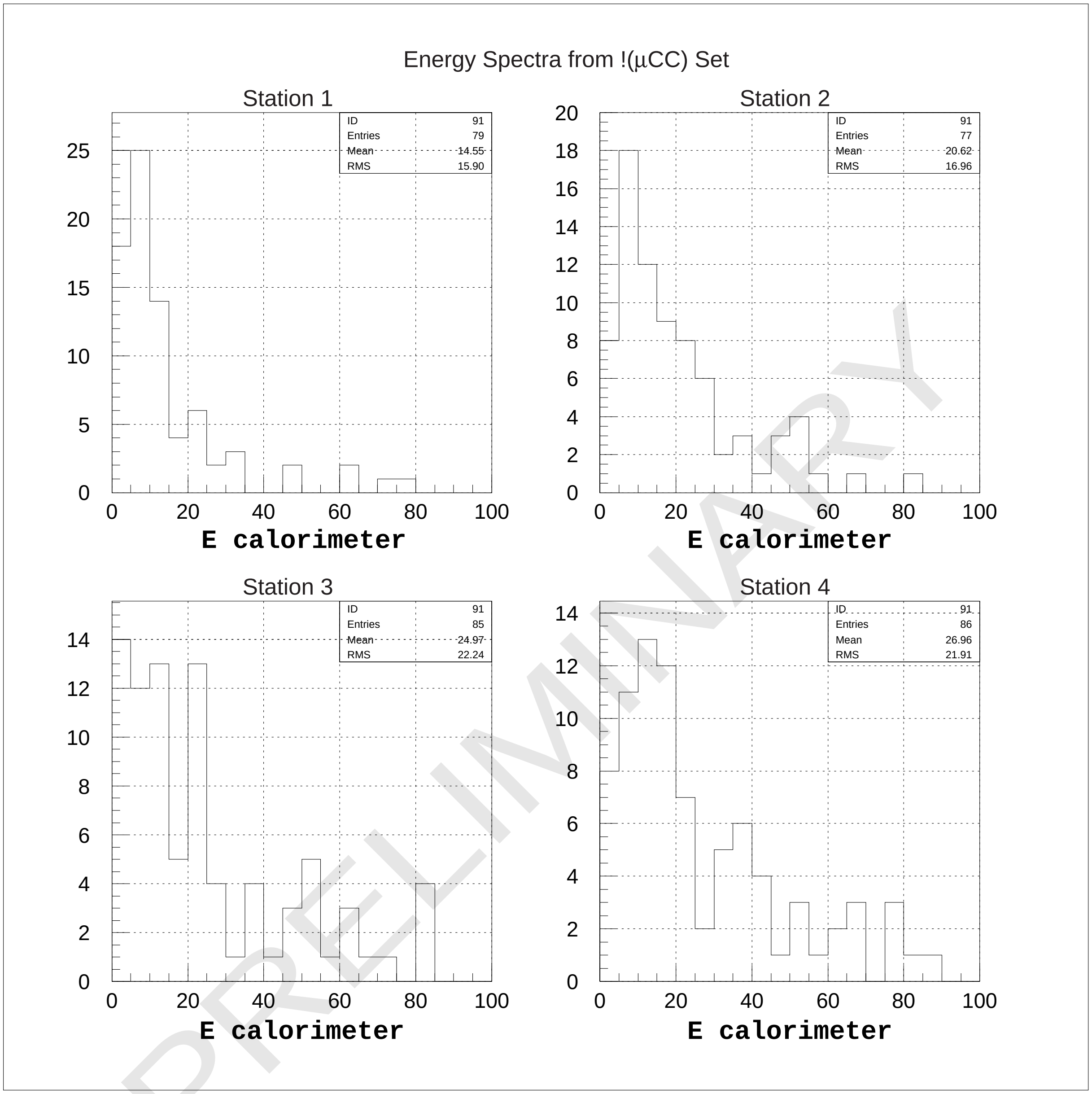

Figure 1. The calorimeter spectra for data with muon events removed.

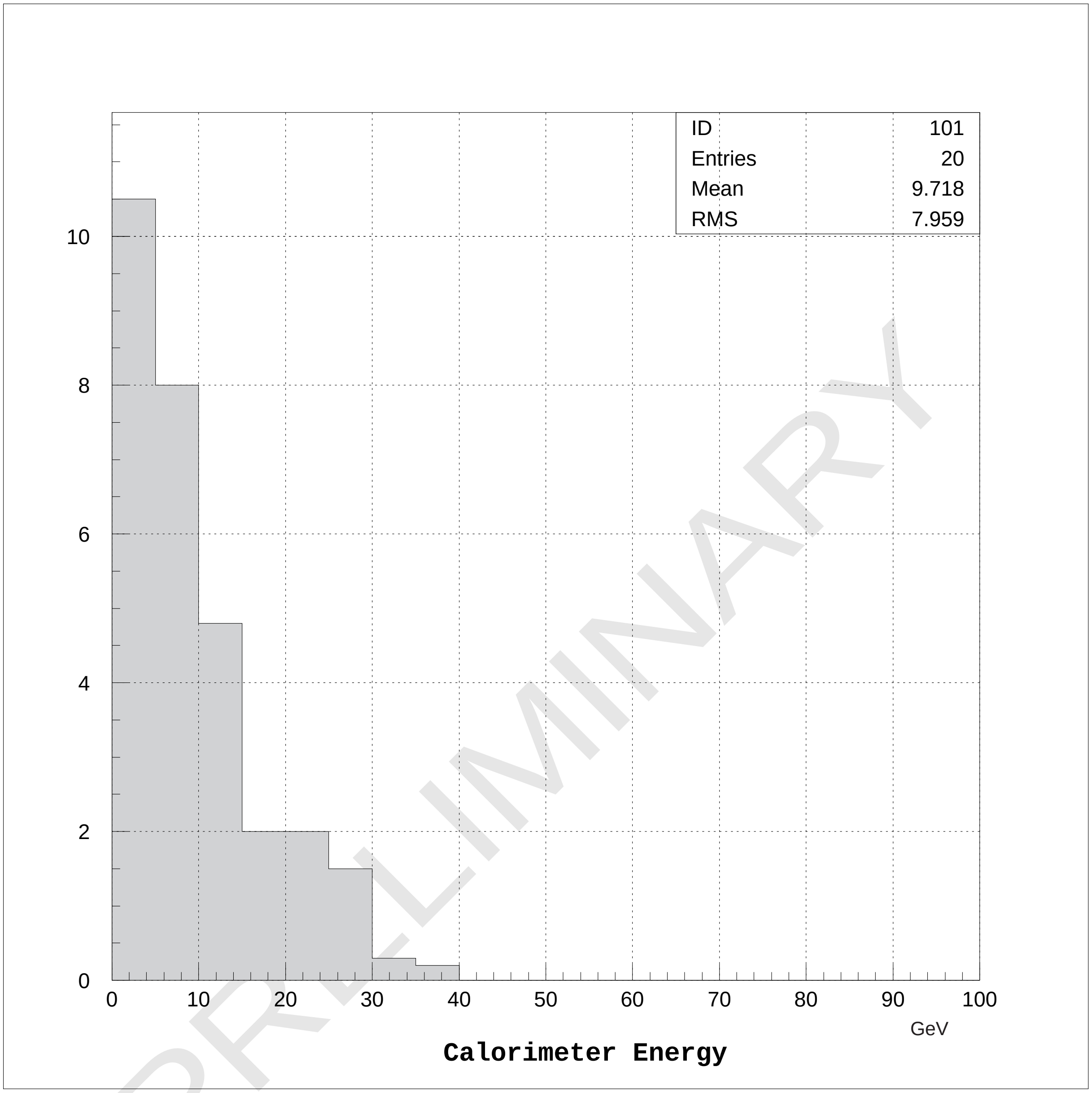

Figure 2. The energy spectrum from nm CC interactions which is assumed to represent the shape of the NC interactions. It is scaled appropriately and subtracted from the non-muon sample of events.

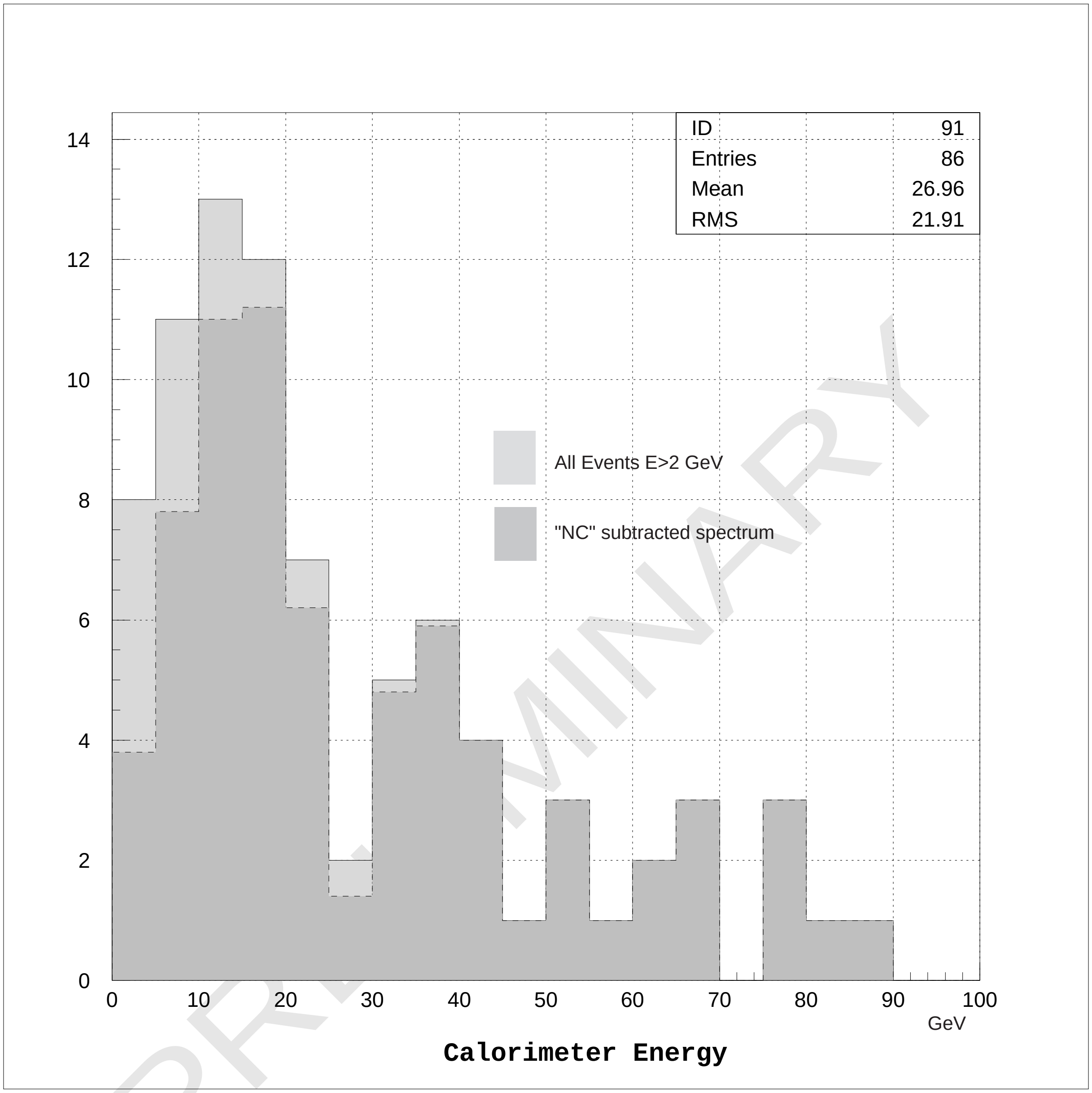

Figure 3. The Station 4 energy spectrum before (*light gray*) and after (*dark gray*) removing the estimated NC component.

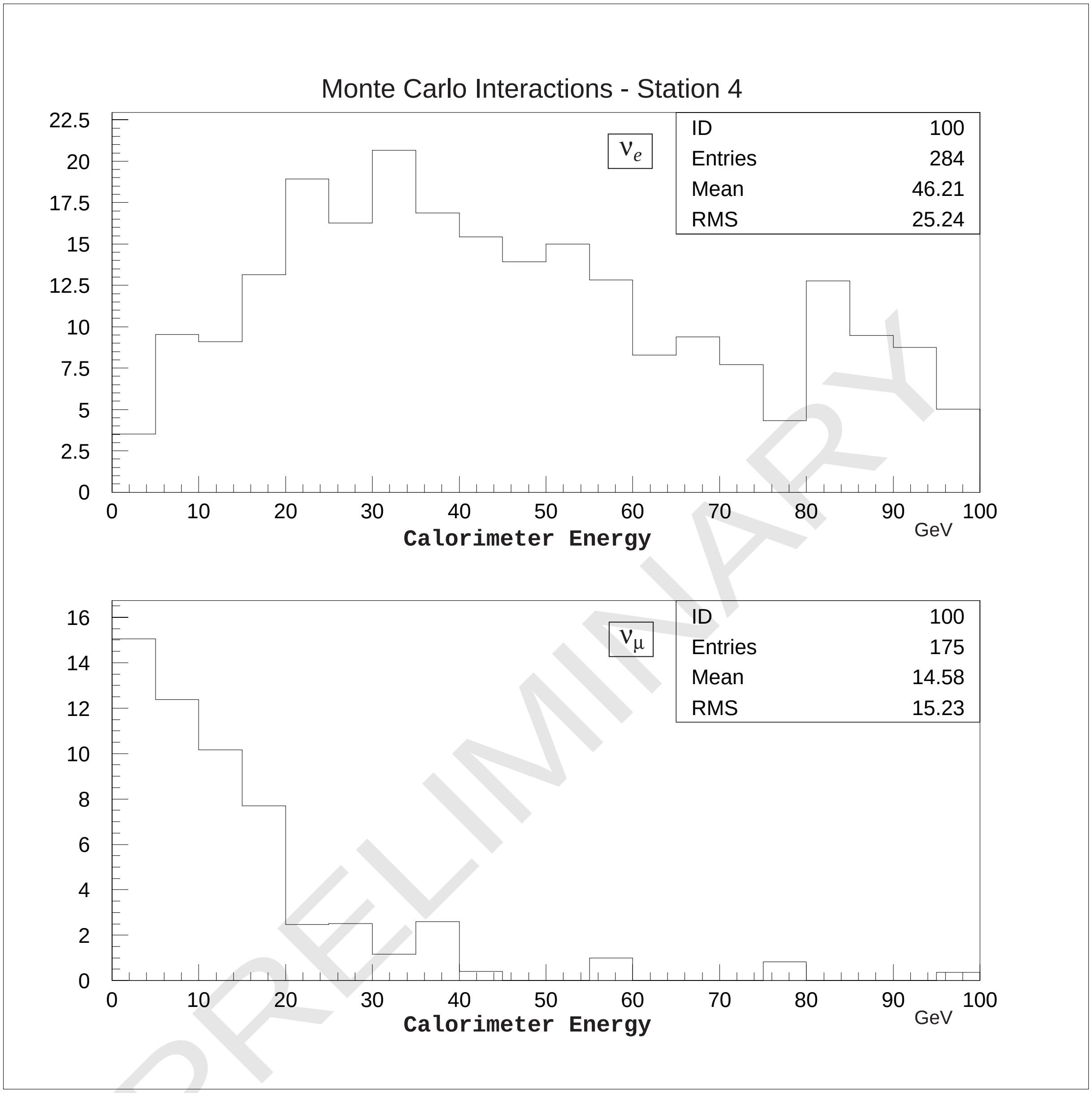

Figure 4. The Monte Carlo energy spectra from ν_e (*top*) and ν_μ CC (*bottom*) interactions in Station 4.

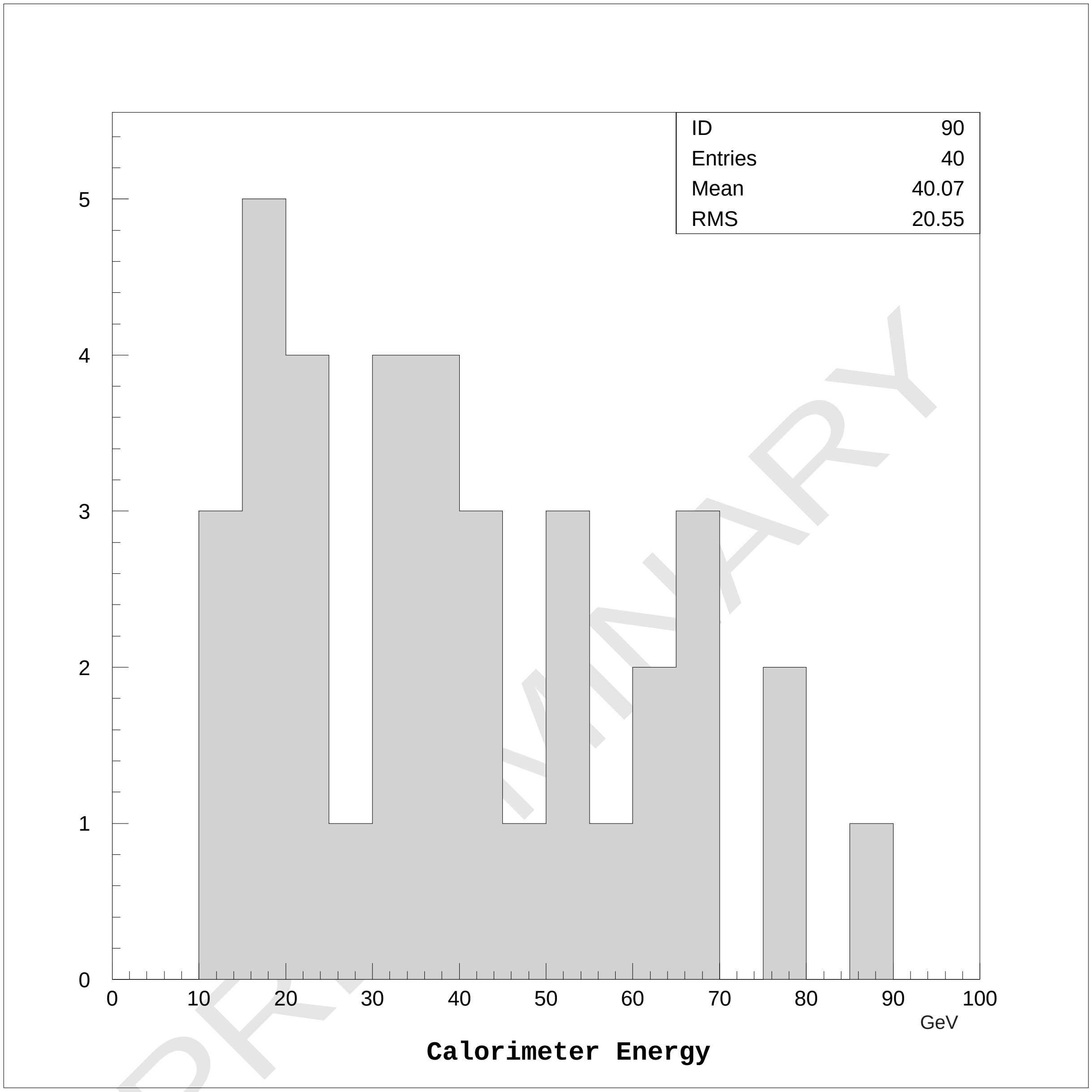

Figure 5. The energy spectrum of events selected as “characteristic” of ν_e CC interactions in Station 4.

Station	! μ	μ	*e*	NC	! ν	Σ
1	95	63				158
2	88	62				150
3	101	54				155
4	129	41	49	25	14	170
Σ	413	220				633

Table showing the number of events per category. For Station 4 the number of electron events is actually the range from 40 to 57 events derived from 3 methods. The number of neutral current events, NC, is derived by subtracting number of electron-like events from the !μ events after the cut $E_{cal} > 2$ GeV. The events remaining, !ν events, are usually low energy, low n_s events and probably are not neutrino interactions.